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TWO-DIMENSIONAL GEOMETRIC OPTIMIZATION OF AN OSCILLATING WATER COLUMN CONVERTER OF REAL SCALE

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Abstract. *The present paper presents a two-dimensional numerical study about the geometric optimization of an ocean Wave Energy Converter (WEC) into electrical energy. The operational principle is based on the Oscillating Water Column (OWC). The main goal is to seek for the optimal geometry which maximizes the absorbed power take off (PTO) when it is subjected to a defined wave climate. To do so, Constructal Design is employed varying the degree of freedom (DOF)* H_1/L *(ratio between the height and length of OWC chamber) and* H_3 *(lip submergence), while the other DOF* H_2/l *(ratio between height and length of chimney) is kept fixed. Moreover, the chamber and total areas of OWC device are also kept fixed, being the problem constraints. In this study was adopted a regular wave with real scale dimensions. For the numerical solution it is used the Computational Fluid Dynamic (CFD) commercial code FLUENT®, based on the Finite Volume Method (FVM). The multiphasic Volume of Fluid (VOF) model is applied to tackle with the water-air interaction. The computational domain is represented by an OWC device coupled with the wave tank. The results led to a theoretical recommendation about the chamber geometry which maximizes the device performance, indicating that the higher efficiency (around 40 %) is obtained when* $H_1/L = 0.13$ *and* $H_3 = 9.50$ *m. On the other hand, the chamber geometry that generate the lower efficiency (around 4.4 %) is formed by* $H_1/L = 0.03$ *and* $H_3 = 9.00$ *m. One can note that the optimal shape is approximately 10 times more efficient than the worst geometry, showing the applicability and relevance of the Constructal Design method in the design of OWC-WEC.*

Keywords: *Constructal Design, wave energy, oscillating water column (OWC), geometric optimization.*

1. INTRODUCTION

Currently one of the greatest challenges is to supply the world energetic demand. In this context, there are several discussions about generation and consumption of electrical energy. One of the main variables to define the development indices of a country is the population's access facility to the infrastructure services, as basic sanitation, transport, telecommunications and energy (ANEEL, 2008).

The global energy consumption in 2011 was approximately 1.6×10^7 MW, which is about 60 % higher than the 1980 energy consumption (Zabihian and Fung, 2011). Moreover, the main source of energy to reach this demand is based on the consumption of fossil fuels.

Very large energy fluxes can occur in deep water sea waves. The power in the wave is proportional to the square of the amplitude and to the period of the motion. Therefore, the long period (~10 s), large amplitude (~2 m) waves represent a considerable interest for power generation, with energy fluxes commonly averaging between 50 and 70 kW/m width of oncoming wave (Twidell and Weir, 2006).

Based on these aspects, recently the countries have been invested in the explanation of new energy sources, especially in so-called renewable energy sources. Among them, the conversion of ocean wave energy into electrical energy has been highlighted. The energy contained in oceans can have different origins, generating different classifications. No doubt, the most relevant are the ocean tidal energy (caused by interaction between the gravitational fields of sun and moon), the ocean thermal energy (direct consequence of solar radiation incidence), the ocean currents energy (originated in the gradients of temperature and salinity and tidal action) and, finally, the ocean wave energy (which is result of the wind effect over the ocean surface) (Cruz e Sarmento, 2004).

The criterion usually adopted to classify the Wave Energy Converter (WEC) devices is related with its installation distance from the coast. In accordance with this classification, the WECs are grouped in: onshore (integrated with

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coastal structures, facilitating the access), near-shore (devices located in depths of 8 to 20m) and offshore (installation depths upper than 25m) (Cruz e Sarmento, 2004).

Another possible classification is associated with the principle adopted to transform the wave energy into electricity, existing three principal groups: Oscillating Water Column (OWC), Wave Activated Bodies (WAB) and Overtopping Devices (OTD). This classification does not end the possibility of other operating principle to be able for convert the ocean wave energy, being an example the submerged plate device (Carter, 2005).

Therefore, the main goal of the present work is to optimize the geometry of an OWC device aiming to improve the incident wave energy harnessing. It is important to mention, that this investigation was conduct considering the operating principle of OWC devices. To do so, it was applied the Constructal Design technique which is based on the Constructal Theory developed by Adrian Bejan (Bejan, 2000; Bejan and Lorente, 2008; Bejan and Zane, 2012; Bejan and Lorente,2013).

The Constructal theory explain deterministically how the generation of shape in flow structures of nature (river basins, lungs, atmospheric circulation, animal shapes, vascularized tissues, etc) is based on an evolutionary principle of flow access in time. That principle is the Constructal law: for a flow system to persist in time (to survive), it must evolve in such way that it provides easier and easier access to the currents that flow through it (Bejan and Lorente, 2008).

Concerning the engineering problems, the Constructal Design (Constructal Theory for optimization of several systems, e.g., engineering) has been broadly applied for the study of fluid mechanics and heat transfer. However, only few works involving the WECs are found in literature.

In Lopes et al. (2011) and Rocha et al. (2013) the Constructal Design was used for the geometric optimization of an OWC-WEC, varying the degree of freedom (DOF) defined by the ratio between the chamber length and the chimney length. In these works, the main purpose was the maximization of mass flow rate of air in the chimney. In addition to this study, Machado et al. (2011) and Rocha et al. (2013) also applied Constructal Design with the purpose to optimize the geometry of an OTD-WEC considering the ratio between the height of the ramp and its length as the DOF analyzed. On both studies the results indicated that the Constructal Design can be used for the WEC's geometrical optimization in a satisfactory way. Moreover, in Gomes et al. (2012) a two-dimensional numerical study about the geometric optimization of an OWC-WEC by means the Constructal Design was performed, where H_1/L (ratio between the height and the length of the OWC chamber) was varied and H_2/l (ratio between the height and the length of the chimney) was kept constant. The OWC chamber area (ϕ_1) and the OWC total area (ϕ_2) are also kept constant, being the problem constraints. For this analysis regular waves in laboratory scale were taken into account. The optimal geometry was defined by $(H_1/L)_o = 0.84$, which is approximately ten times more efficient than the worst geometry ($H_1/L = 0.14$).

So, in the present work the Constructal Design was applied to an OWC-WEC device subjected to a regular incident waves in real scale. To do so, the variation of H_1/L (ratio between the height and the length of its chamber) and H_3 (its lip submergence) was considered. The objective function is to maximize the harnessing of incident wave power, i.e., the conversion of this power into hydropneumatic power. The other DOF H_2/l (ratio between the height and length of the chimney) was kept fixed, as well as, the OWC chamber area (ϕ_1) and the OWC total area (ϕ_2), which are the two problem geometric constraints.

The computational domain (OWC coupled to a wave tank) was created and discretized in GAMBIT® software, while the numerical simulations were carried out by means a computational modeling implemented in the Computational Fluid Dynamic (CFD) commercial software FLUENT®, which is based on the Finite Volume Method (FVM) (FLUENT, 2007; Versteeg and Malalasekera, 2007). The multiphase Volume of Fluid (VOF) model was employed for the treatment of water-air interaction, as already performed by: Gomes (2010), Horko (2007), Liu et al. (2008a), Liu et al. (2008b), Liu et al. (2011) and Ramalhais (2011). The wave generation was promoted by the imposition of the vertical and horizontal velocity wave components as boundary condition.

2. COMPUTATIONAL MODELING OF OWC DEVICES

2.1 Oscillating Water Column

The Oscillating Water Column devices are, basically, hollow structures partially submerged, with an opening to the sea below the water free surface, as can be seen in Fig. 1. In accordance with Cruz and Sarmento (2004), the electricity generation process has two stages: when the wave reaches the structure, its internal air is forced to pass through a turbine, as a direct consequence of the augmentation of pressure inside the chamber; and when the wave returns to the ocean, the air again passes by the turbine, but now being sucked from the external atmosphere, due to the chamber internal pressure decreasing. So, to use these opposite air movements usually the Wells turbine is employed, which has the property of maintaining the rotation direction irrespective of the flow direction. The set turbine/generator is the responsible for the electrical energy production.

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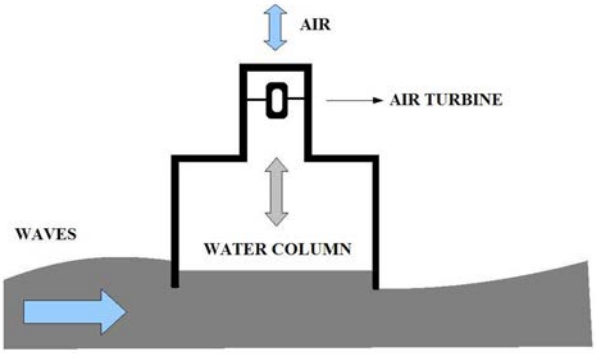

Figure 1. Oscillating water column system

2.2 Computational Domain

Based on the of the period (*T*), height (*H*) and propagation depth (*h*) of the wave, it is possible to define the length (L_T) and height (H_T) of the wave tank (Fig. 2). There is no a general rule to establish these dimensions, however some aspects must be taken into account. The wave propagation depth is adopted as the wave tank mean water level, i.e., the wave tank water depth (*h*). For the wave tank length it is necessary to consider the wave length, being recommended that the wave tank length has at least five times the wave length. Thereby, a numerical simulation without effects of wave reflection can be performed, during a satisfactory time interval and without an unnecessarily increase of the computational domain length (which would cause an increase in the computational effort and in the processing time). Regarding the wave tank height, the propagation depth and the height of the wave must be considered. So, it is possible to define the wave tank height as the propagation depth plus three times the wave height.

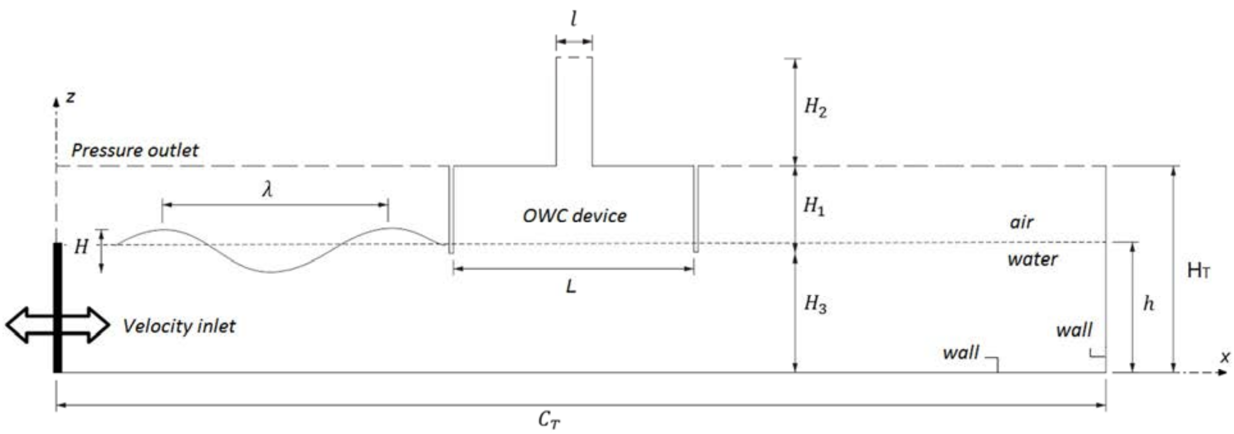

Figure 2. Schematic representation of the computational domain

With respect to the tank height it is necessary take into account the water depth (*h*) and the wave height (*H*). It is suggested that the tank height must be equal to the value of water depth plus three times the value of wave height. Therefore all the characteristic dimensions of the problem are presented in Tab. 1. It is important to emphasize that the H_3 dimension varies in relation to *H* and hence several values for the OWC-WEC lip submergence were tested: 10.25 m, 10.00 m, 9.75 m, 9.50 m, 9.25 m and 9.00 m.

Table 1. Characteristic dimensions of the problem.

Characteristic Dimensions	Values
Wave period (*T*)	5.0 s
Wave height (*H*)	1.0 m
Wave length (*λ*)	37.6 m
Wave propagation depth (*h*)	10.0 m
Wave tank length (L_T)	188.0 m
Wave tank height (H_T)	13.0 m
OWC Lip (H_3)	variable

As can be observed in Fig. 2, the wave maker is placed in the left side of the wave tank. For the regular wave generation it was employed the called Function Methodology (Gomes et al. 2009). This methodology consists of applying the horizontal (u) and vertical (w) components of wave velocity as boundary conditions (velocity inlet) of the computational model, by means an User Defined Function (UDF) in the FLUENT® software. These velocity components vary as functions of space and time and are based on the Linear Theory. So these wave velocity components are given by:

$$u = \frac{H}{2} gk \frac{\cosh(kz+kh)}{\omega \cosh(kh)} \cos(kx-\omega t) \tag{1}$$

$$w = \frac{H}{2} gk \frac{senh(kz+kh)}{\omega \cosh(kh)} sen(kx-\omega t) \tag{2}$$

where: H is the wave height (m); g is the gravitational acceleration (m/s^2); λ is the wave length (m); k is the wave number, given by $k = 2\pi/\lambda$ (m^{-1}); h is the depth (m); T is the wave period (s); ω is the frequency, given by $\omega = 2\pi/T$ (rad/s); x is the streamwise coordinate (m); t is the time (s); and z is the normal coordinate (m).

Concerning the other boundary conditions, in the upper surfaces of wave tank and chimney and above the wave maker (dashed line in Fig. 2) it was considered the atmospheric pressure (pressure outlet). In the bottom and right side of computational domain a no slip and impermeability conditions (wall) were adopted.

In all numerical simulations the mesh follows a pattern where a special refinement is employed in some specific regions of the computational domain. As can be observed in Fig. 3, in the vertical direction the wave tank is divided in three regions nominated A, B and C. In the water free surface region (B region) it is adopted a refinement with 40 volumes in z direction (interval size equivalent to H/20) and with 250 volumes in the x direction (interval size equivalent to λ/50). Furthermore 10 and 90 volumes are used in z direction for the spatial discretization of A and C regions, respectively, in accordance with Barreiro (2009). To complete the computational domain mesh, squares with 0,1 m were used in the OWC discretization.

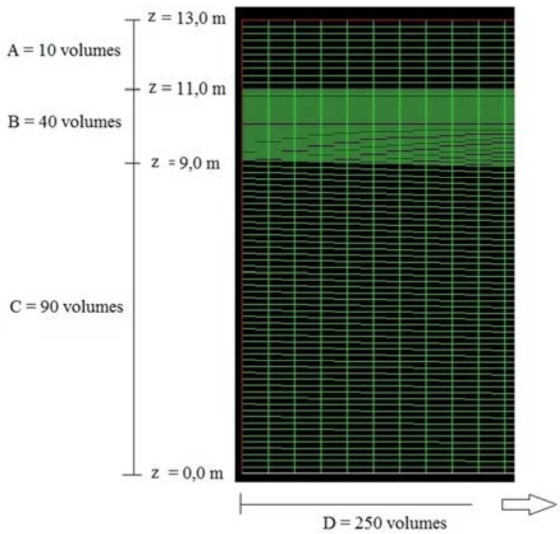

Figure 3. A, B ,C and D regions used in the computational domain discretization.

3. CONSTRUCTAL DESIGN FORMULATION OF OWC-WEC DEVICE

Basically, to apply the Constructal Design for the geometric optimization of a physical system it is required an objective function (a quantity that will be optimized), degrees of freedom (geometric parameters which may vary during the optimization process) and geometric constraints (parameters that are kept constant during the optimization process).

In the present work the objective function was to maximize the OWC available power, varying the dof H_1/L (ratio between the height and length of the chamber) and the dof H_3 (lip submergence) (see Fig. 2). Two global constraints were considered: the OWC chamber area (ϕ_1) and the OWC total area (ϕ_2), which are defined as:

$$\phi_1 = H_1 L \tag{3}$$

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$$\phi_2 = \phi_1 + H_2\, l \tag{4}$$

Besides, the other DOF H_2/l (ratio between the height and the length of the chimney) was kept constant for all numerical simulations.

4. MATHEMATICAL AND NUMERICAL MODELS

The Volume of Fluid (VOF) method is a multiphase numerical model that can be used to treat the interaction between water and air inside the wave tank. In this method, the free surface can be identified by the volume fraction (*f*) variable. In each mesh cell (volume), if $f = 1$ the cell is full of water, when $f = 0$ the cell contain only air and if $0 < f < 1$ the cell has water and air simultaneously. Moreover, when the VOF method is used a single set of momentum and continuity equations is applied to all fluids, and the volume fraction of each fluid in every computational cell (control volume) is tracked throughout the domain by the addition of a transport equation for the volume fraction. Thus, the model is composed by the continuity, momentum and volume fraction equations, which are respectively given by (FLUENT, 2006; Gomes et al., 2009):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v}\right) = 0 \tag{5}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{v}\right) + \nabla \cdot \left(\rho \vec{v}\vec{v}\right) = -\nabla p + \nabla \cdot \left(\bar{\bar{\tau}}\right) + \rho \vec{g} \tag{6}$$

$$\frac{\partial (f)}{\partial t} + \nabla . \left(f \vec{v}\right) = 0 \tag{7}$$

being: ρ the fluid density (kg/m^3), t the time (s), $\vec{v}$ the flow velocity vector (m/s), p the static pressure (Pa), $\bar{\bar{\tau}}$ the stress tensor (Pa) and $\vec{g}$ the gravitational acceleration (m/s^2).

The solver is pressure-based and all simulations were performed by upwind and PRESTO for spatial discretizations of momentum and pressure, respectively. The velocity-pressure coupling is performed by the PISO method, while the GEO-RECONSTRUCTION method is employed to tackle with the volumetric fraction. Moreover, under-relaxation factors of 0.3 and 0.7 are imposed for the conservation equations of continuity and momentum, respectively. All numerical simulations were carried out in a computer AMD Athlon 2 Core with 3.0Gb of RAM. To reduce the simulation time the parallel processing technique was adopted (FLUENT, 2006).

5. RESULTS AND DISCUSSIONS

Computational modeling using the VOF method has been largely employed to numerically simulate the WECs. Validations and verifications of these methodologies can be found in Horko (2007), Liu et al. (2008a), Liu et al. (2008b), Gomes et al. (2009), Gomes (2010), Ramalhais (2011), Liu et al. (2011) and Gomes et al. (2012).

In this work the computational model verification was performed comparing the transient water free surface elevation in a specific position numerically obtained with the respective analytical solution, which is defined by:

$$\eta = A \cos\left(kx - \omega t\right) \tag{8}$$

where: A is the wave amplitude (m), given by $H/2$.

As already described in section 2, in all numerical simulations a mesh with a special refinement in the water free surface region was adopted. So, to verify the numerical solution accuracy three tests were carried varying the time step value, as showed in Tab. 2.

Table 2. Time step test and numerical solution accuracy.

T	Time step (s)	Monitor 1			Monitor 2		
		Difference [%]			Difference [%]		
		maximum	minimum	average	maximum	minimum	average
5 s	*T* / 1000	7,71	-5,83	2,87	23,0	-18,1	7,16
	T / 800	7,78	-5,81	2,88	23,0	-18,1	7,20
	T / 500	5,23	-5,12	2,69	7,59	-10,7	4,84

The monitors 1 and 2 are placed in x = 37.6 m and x = 73.2 m, respectively, from the left side of computational domain, i.e., from the wave maker (see Fig. 2). Besides, the results of the verification process (Tab. 3) were obtained considering only the interval time in which the numerical wave generation is already stable. For this the interval time between the propagation of the third and the sixth waves was used: 15 s $\leq t \leq$ 30 s. It is worthy to mention that wave reflection effects does not occurred during this interval time. These results indicate that a time step of T/500 can be used, since the numerical solution accuracy is preserved.

In Fig. 4 one can observe the qualitative behavior of the wave propagation, showing a good agreement between the numerical and analytical solutions. During the interval time mentioned above (15 s $\leq t \leq$ 30 s) the maximal difference encountered was 5.23 %, verifying the computational model for the wave generation.

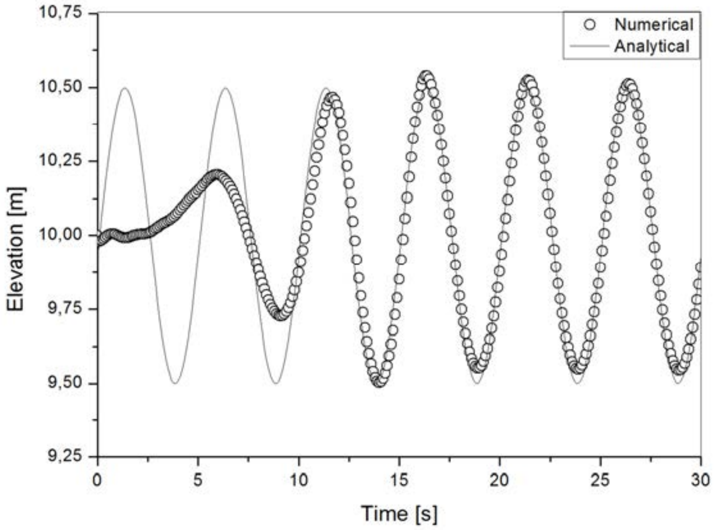

Figure 4. Water free surface elevation in x = 50 m with time step of T/500.

To employ the Constructal Design method it is required taken into account the constraints ϕ_1 and ϕ_2 which are defined by Eq. (2) and Eq. (3). Initially it was considered $H_1 = H$, obtaining a ϕ_1 value that represents 70 % of the OWC-WEC total area (ϕ_2).

These parameters are kept constant in all simulations with values of: ϕ_1 = 37.6, ϕ_2 = 53.7143 and H_2/l = 3.0. Thus, varying the degree of freedom H_1/L it was possible to calculate the OWC-WEC dimensions, being these values showed in Tab. 3. Highlighting that for the choice of ϕ_1 value was taken into account the initial situation (Case 1), in which the OWC length (L) is equal to the length (λ) of incident wave.

Table 3. OWC-WEC geometry variations for T = 5 s and ϕ_1 = 37.6.

Case	H_1/L	L [m]	H_1 [m]	l [m]	H_2 [m]
1	0.0266	37.5969	1.0000	2.3176	6.9529
2	0.0399	30.6978	1.2248	2.3176	6.9529
3	0.0598	25.0646	1.5001	2.3176	6.9529
4	0.0897	20.4652	1.8372	2.3176	6.9529
5	0.1346	16.7097	2.2501	2.3176	6.9529
6	0.2019	13.6434	2.7558	2.3176	6.9529
7	0.3029	11.1398	3.3752	2.3176	6.9529
8	0.4544	9.09564	4.1338	2.3176	6.9529
9	0.6817	7.42656	5.0629	2.3176	6.9529
10	1.0225	6.06376	6.2007	2.3176	6.9529

For each case of Tab. 3 were tested five different values of OWC-WEC lip submergence (H_3), as shown in Tab. 4. One can note that H_3 has its variation related with the wave height (H). After these tests an "optimal" recommendation for the DOF´s H_1/L and H_3 will be done.

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Table 4. H_3 dimension variations.

H_3	measure
h	10,00 m
h - $H/4$	9,75 m
h - $H/2$	9,50 m
h - $3H/4$	9,25 m
h - H	9,00 m

It were evaluated the mass flow rate (in the chimney outlet), the pressure (inside the chamber), as well as the OWC hydro-pneumatic power, considering a time interval of 15 s $\leq t \leq$ 30 s. The average values were calculated employing the Root Mean Square (RSM) which is a statistical technique applied for varying quantities and is given by (Marjani et al., 2006):

$$X = \sqrt{\frac{1}{T}\int_0^T x^2\, dt} \tag{9}$$

The RMS values for the mass flow rate, $\dot{m}$ (kg/s), the pressure, P (Pa), and hydro-pneumatic power, P_{hyd} (W), are showed in Tab. 5. It is worth to mention that any flow restriction representing the head loss caused by the turbine was not considered. So, the available hydro-pneumatic power was evaluated by (Dizadji and Sajadian, 2011):

$$P_{hyd} = \left(P_{air} + \frac{\rho_{air} v_{air}{}^2}{2} \right) \frac{\dot{m}}{\rho_{air}} \tag{10}$$

where: P_{air} is the static pressure in the OWC chimney (Pa), ρ_{air} is the air density (kg/m^3), $\dot{m}$ is the air mass flow rate crossing the chimney (kg/s), v_{air} is the air velocity in the chimney (m/s) given by:

$$v_{air} = \frac{\dot{m}}{A\rho_{air}} \tag{11}$$

being A the cross sectional area of the chimney.

Another aspect it was considered in the present study is the OWC-WEC efficiency. According to Gomes (2010) this efficiency can be defined by the ratio between the hydro-pneumatic power (absorbed by the device) and the power o incident wave, P_i (W), which is given by McCormick (1981):

$$P_i = \frac{\rho\, g}{8} H^2 c_g b \left[1 + \frac{9}{64} \frac{H^2}{k^4 h^6} \right] \tag{12}$$

where: ρ is the water density (998.2 kg/m^3), g is the gravity acceleration (9.81 m/s^2), c_g is the wave celerity (m/s), b is the OWC-WEC width (m) and k is the wave number. So, applying the Eq. (12) for the incident wave adopted in this work a power per unit of wave front of 5,692.64 W was obtained. As an two-dimensional numerical approach was considered, the value of wave width is unitary in all cases.

In Tab. 5 are presented the hydro-pneumatic power absorbed by the OWC-WEC device during the propagation of the sixth wave, called $P_{hyd,6T}$ (W), and the OWC-WEC efficiency, denoted by ε (%), for each studied case.

Based on the obtained results (Tab. 5), when the DOF H_1/L is varied the RMS values for the mass flow rate, pressure and hydro-pneumatic power are concentrated between cases 3 and 7, i.e., between lengths of 25.0646 m and 11.1398 m for the OWC-WEC, representing approximately 2/3 and 1/4 of the length of the incident wave, respectively. This fact becomes more evident analyzing the Fig. 5. Therefore, it is obvious that the OWC-WEC length has a strong relation with the length of incident waves. However, a small redistribution in the OWC-WEC inlet geometry can lead a better system performance. This trend is in consonance with the Constructal theory which states that for a flow system evolve the imperfections tend to be redistributed (Bejan and Zane, 2012).

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Table 5. Results for mass flow rate, pressure, power and efficiency.

H_3 = 10.25 m						H_3 = 10.00 m					
H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε	H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε
0.0266	6.13	14.93	19.11	306.38	5.38	0.0266	6.17	16.02	21.56	305.48	5.36
0.0399	8.51	16.24	29.66	461.68	8.11	0.0399	9.33	17.58	37.77	521.81	9.16
0.0598	11.12	21.28	54.53	1030.95	18.11	0.0598	12.87	25.19	79.71	1463.95	25.71
0.0897	12.07	22.75	63.84	1292.45	22.70	0.0897	14.33	27.41	98.39	1917.41	33.68
0.1346	11.94	21.81	61.54	1249.97	21.95	0.1346	14.29	27.26	90.05	1743.97	30.63
0.2019	11.44	22.36	55.66	1122.45	19.71	0.2019	13.54	26.44	79.98	1603.99	28.17
0.3029	10.63	22.37	45.62	910.25	15.99	0.3029	12.49	24.73	72.02	1479.10	25.98
0.4544	9.64	18.75	39.76	786.79	13.82	0.4544	11.16	22.50	58.13	1181.83	20.76
0.6817	8.50	16.33	30.96	611.77	10.74	0.6817	9.62	19.17	41.96	847.59	14.88
1.0225	7.35	14.27	23.78	462.86	8.13	1.0225	8.24	16.04	30.04	605.82	10.64
H_3 = 9.75 m						H_3 = 9.50 m					
H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε	H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε
0.0266	5.75	17.56	19.50	197.25	3.46	0.0266	6.33	18.09	25.39	316.39	5.55
0.0399	8.77	18.71	35.79	368.87	6.47	0.0399	8.97	27.12	54.23	917.31	16.11
0.0598	12.83	23.40	71.07	1205.01	21.16	0.0598	12.44	23.24	66.45	1189.01	20.88
0.0897	15.02	28.01	112.08	2110.80	37.07	0.0897	14.71	26.91	103.38	1977.68	34.74
0.1346	15.31	29.08	114.70	2263.29	39.75	0.1346	15.22	28.66	116.43	2282.46	40.09
0.2019	14.63	28.66	104.79	2077.05	36.48	0.2019	14.62	28.63	109.51	2149.88	37.76
0.3029	13.42	26.69	89.29	1831.32	32.17	0.3029	13.36	26.45	92.48	1855.91	32.60
0.4544	11.79	23.58	68.67	1384.23	24.31	0.4544	11.78	23.19	70.68	1446.10	25.40
0.6817	10.15	19.93	47.57	981.30	17.23	0.6817	10.19	20.15	50.80	1050.81	18.45
1.0225	8.58	16.82	33.12	674.85	11.85	1.0225	8.66	17.20	35.88	730.86	12.83
H_3 =9.25 m						H_3 = 9.00 m					
H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε	H_1/L	$\dot{m}$	P	P_{hyd}	$P_{hyd,6T}$	ε
0.0266	6.72	26.88	37.08	568.02	9.97	0.0266	5.32	9.38	11.88	250.27	4.39
0.0399	9.05	21.23	42.95	319.47	5.61	0.0399	7.69	19.31	37.39	475.97	8.36
0.0598	12.48	37.91	113.04	2260.50	39.70	0.0598	11.83	28.17	68.93	956.04	16.84
0.0897	14.54	26.85	100.39	1909.06	33.53	0.0897	14.38	27.61	98.51	1932.90	33.95
0.1346	15.15	28.36	114.23	2238.81	39.32	0.1346	15.05	28.01	113.44	2207.60	38.77
0.2019	14.62	28.35	108.67	2136.65	37.53	0.2019	14.62	28.01	108.83	2118.51	37.21
0.3029	13.45	26.55	93.50	1892.79	33.24	0.3029	13.53	26.53	94.17	1868.97	32.83
0.4544	11.90	23.38	71.95	1465.92	25.75	0.4544	12.07	23.66	74.02	1508.25	26.49
0.6817	10.35	20.52	52.79	1099.37	19.31	0.6817	10.53	20.87	54.69	1138.94	20.00
1.0225	8.82	17.58	37.46	764.91	13.43	1.0225	9.00	17.98	39.23	816.46	14.34

Another important observation in Tab. 5 and Fig. 5 is about the DOF H_3. It is evident that for the OWC-WEC lip submergence values located below the mean water level (h = 10.00 m) there is a considerable improvement in the performance device, hence reaching more elevated efficiency values. The best case was obtained when H_3 = 9.50 m, with a RMS value of hydro-pneumatic power of 116.43 W and a efficiency of 40 %, while the worst case was defined by H_3 = 10.25 m, P_{hyd} = 63.84% and ε = 23 %. Again, a small geometric variation generates an improvement of almost two times in the system efficiency between the best and worst studied cases, showing that the Constructal Design can be used in the search of better performances in WEC devices.

In the present work the study was conducted in order to obtain a theoretical recommendation about the geometric configuration of an OWC-WEC device aiming to maximize the incident wave energy harnessing and hence to contribute for the generation of a higher amount of electrical energy.

In Fig. 6a it is possible to note that the geometric configurations obtained by the ratio H_1/L=0.13, i.e., when L is approximately 0.5λ, are in most cases which present the best RMS values for the hydro-pneumatic power. This trend corroborates the results shown in Fig. 5. On the other hand, still considering the Fig. 6a, when the geometries for the OWC-WEC has a ratio of H_1/L = 0.03 (when L is approximately 0.82λ), small RSM values for the hydro-pneumatic power were obtained. Thus, one can note that a good relation between the OWC length and the wave length is when L = 0.5λ.

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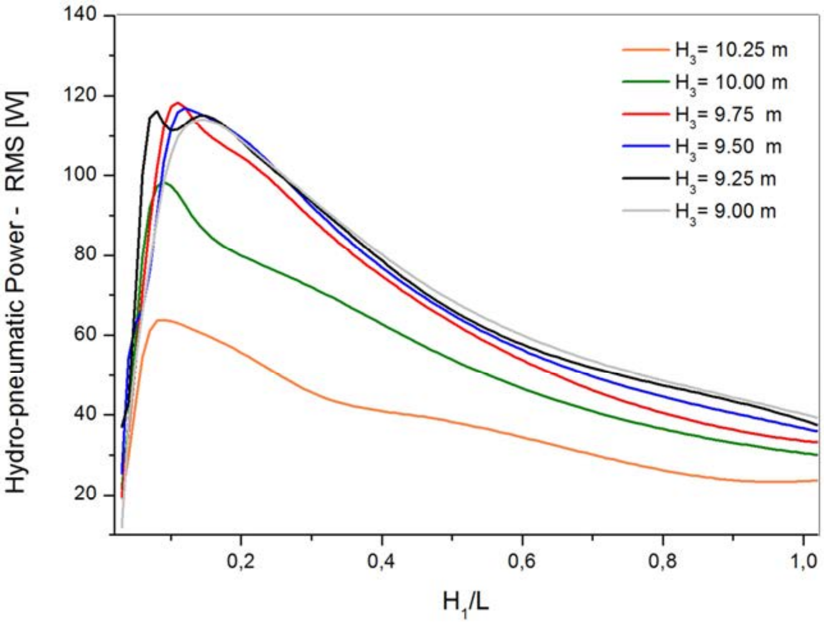
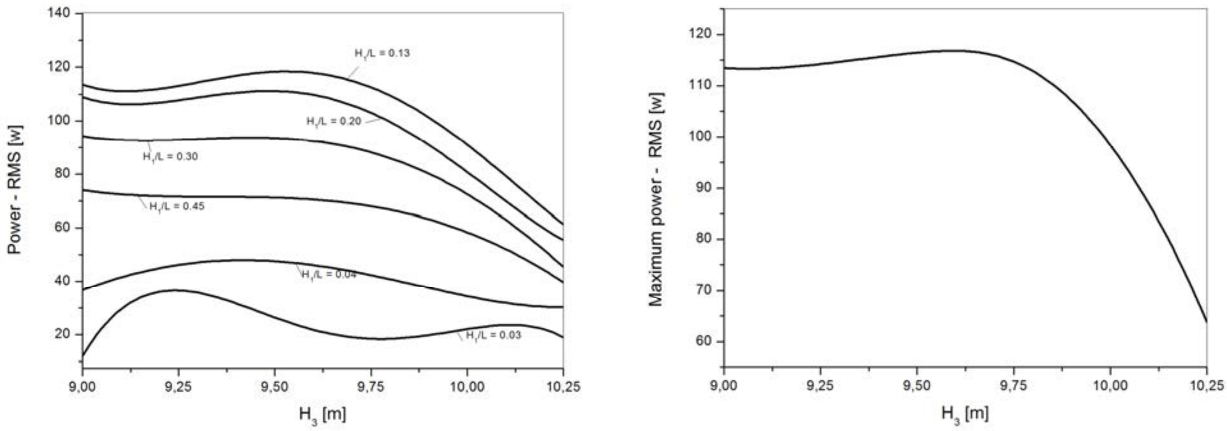


Figure 5. RMS value for the hydro-pneumatic power variation in relation to H_1/L.

Further important aspect to be analyzed from Fig. 6a is the behavior of the RMS value of hydro-pneumatic power in relation to the H_3 variation. The results revealed that, in general, the decrease of H_3, i.e., when the OWC-WEC is more submerged, leads to an increase of the RMS value of hydro-pneumatic power, except for the lowest magnitude of H_1/L = 0.03 where it is noticed a strong reduction of RMS power for H_3 = 9.0 m. In Fig. 6b the same trend can be observed, however it is considered the once maximized RMS power for each ratio H_1/L, evidencing that the best designs for the OWC-WEC chamber are achieved for lower values of H_3. More precisely, the best performance is noticed for $(h\text{-}H/4) > H_3 > (h\text{-}H)$ (9.75 m > H_3 > 9.00m) where the OWC performance is almost constant (Fig. 6b). This behavior is important for design of OWC-WEC device, once in the real conditions the mean water free surface vary. However, in this range of H_3 the OWC-WEC will operate with maximum efficiency.



(a) (b)

Figure 6. RMS value for the hydro-pneumatic power variation in relation to H_3: (a) H_1/L kept constant; (b) Maximum power for each H_1/L in relation to H_3.

As already mentioned, main goal of this work is to present a theoretical recommendation enabling to define the optimal dimensions of the OWC-WEC chamber in relation to the wavelength of the incident waves by means the variation of the H_1/L, as well as, to determine the optimal value for the OWC-WEC lip submergence (H_3) also in relation to the wavelength of the incident waves, aiming to reach the best performance of the device. In this sense, in accordance with depicted in Fig. 7, and having as objective function the RSM value for the hydro-pneumatic power, the optimal geometry is obtained when H_1/L = 0.13 and $(h\text{-}H) \leq H_3 \leq (h\text{-}H/4)$.

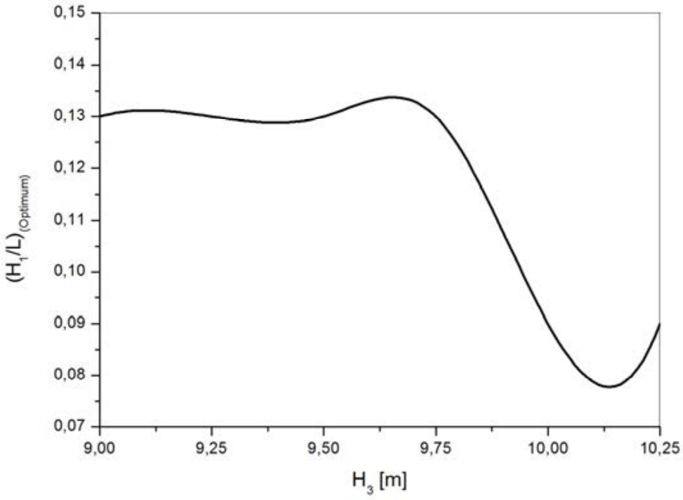


Figure 7. Geometric optimization of H_1/L in relation to H_3.

Finally, comparing all obtained results, which are presented in Tab. 5, the geometric configuration with the highest efficiency occurs when H_1/L = 0.13 and H_3 = 9.50 m, while the lowest efficiency is obtained when H_1/L=0.03 and H_3 = 9.00 m. Thus, in Fig. 8, the behavior of the air mass flow rate in the outlet of chimney for these cases are compared. One can note that the air mass flow rate can reach differences larger than 2 kg/s. Hence, during all simulation time, the mass of air that flowed through the OWC-WEC chimney was of 7,000 kg in the worst case while in the best case this value achieves 12,000 kg, representing an improvement in the air flux around 72 %. It is worth to mention that, keeping constant the OWC-WEC total area, only a simple geometrical redistribution was performed to obtain these results.

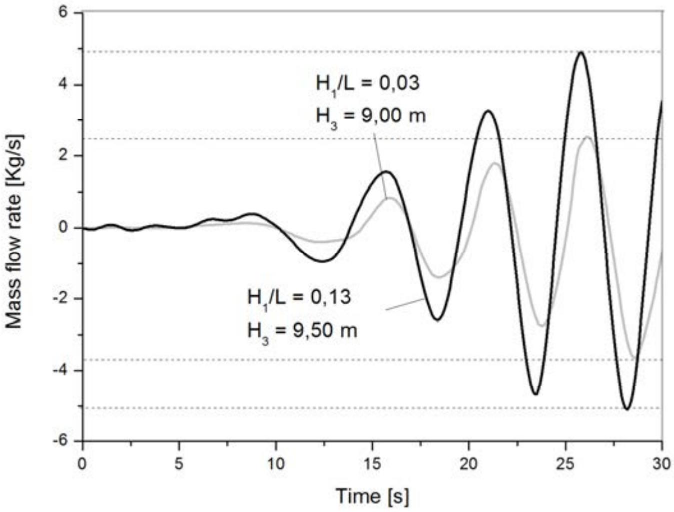


Figure 8. Air mass flow rate behavior for the best and worst cases.

6. CONCLUSIONS

In the present work a numerical study was carried out aiming to define optimal geometry of an Oscillating Water Column (OWC) Wave Energy Converter (WEC). To do so, the Constructal Design method (based on the Contructal Theory, developed by Adrian Bejan in 1997) was used to define several geometry variations, enabling to define which one leads to the best perfomance of the device. So, the main goal was to obtain a theoretical recommendation about the values for the degrees of freedom H_1/L and H_3 that enable to achieve a more elevated OWC-WEC efficiency, when the device is subjected to incidente waves with period of 5s and wavelength of 37.6 m.

Te optimal ratio H_1/L, i.e., the value of H_1/L which generate the maximum RSM value for the OWC-WEC hydro-pneumatic power was obtained when $(H_1/L)_o$ = 0.13 ($L \cong 7.7\, H_1$) or also $L = 0.5\,\lambda$. After that, still considering the maximum RSM value for the hydro-pneumatic power, the H_3 dimension was optimized. The results indicated that there is a range for the H_3 dimension, $(h\text{-}H) \le H_3 \le (h\text{-}H/4)$, in which the ratio H_1/L is almost kept constant and equal to 0.13, reaching the maximum efficiency of the OWC-WEC studied.

Besides, the geometric configuration that has the more elevated efficiency (around 40 %) is defined when $H_1/L = 0.13$ and $H_3 = 9.50\ m$, while the one which presents the worst efficiency (around 4 %) is obtained for $H_1/L=0.03$ and $H_3 = 9.00\ m$. Therefore, an improvement of ten times can be reached with only a simple geometrical redistribution, showing the applicability of the Constructal Design method in this kind of engineering problem.

These results are very promising because they provide a theoretical recommendation about the optimal geometry of an OWC-WEC device which allows the incident waves harnessing maximization. Moreover, in accordance with the Constructal formulation adopted, it is possible to relate the OWC-WEC dimensions with the incident waves characteristics. So, if the wave climate is known it is possible to design the OWC-WEC for a specific region reaching its best performance.

7. ACKNOWLEDGEMENTS

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